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Human Visual Limitations on Suprathreshold Contrast Perception Through ANVIS

By

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Sensory Research Division

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Recent success on the battlefield underscored the tactical advantage of night operations and image intensifying devices. It is important to understand both the benefits and limitations inherent in these devices. While several studies have focused on spatial resoultion thresholds through image intensifiers, less is known about visual perception at suprathreshold levels of stimulation. Such information is necessary to anticipate and predict visual performance under various conditions. In this study contrast matching was used to evaluate suprathreshold visual perception under conditions which simulated the luminance, contrast, and chromaticity of third generation image intensifiers contained in the Aviator's Night Vision Imaging System (ANVIS). The apparent contrast of letters in this simulated ANVIS environment was reduced by a factor of two when compared to normal photopic levels of stimulation. This effect was attributed to limitations of the human visual system in processing higher spatial frequencies at low light levels. These results help to quantify and discriminate between visual and electro-optical limitations on vision through image intensifiers.

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Introduction

The recent success of U.S. forces in Operation Desert Storm has reinforced Army doctrine of airland battle and night operations. Both tactical and support maneuvers frequently occur at night or under conditions of limited visibility. Hence, we depend critically on image intensifying devices to allow us to perform under extreme and limited conditions. Despite substantial intensification of the image, these devices present an isochromatic view of the world often lacking in contrast and detail (Wiley, Glick, and Holly, 1983). It is incumbent upon us to define the limitations on vision with image intensifying devices so that performance can be anticipated and predicted under various conditions.

Spatial aspects of vision through image intensifying devices have been quantified in several studies in terms of threshold measurements such as visual acuity and contrast sensitivity (Wiley and Holly, 1976; Wiley, 1989; Levine and Rash, 1989; Riegler et al., 1991; Kotulak and Rash, 1992). Less is known, however, about visual perception at suprathreshold levels of stimulation. Such information would be useful to better understand how objects are detected and recognized at intensities and contrasts expected in operational environments.

In this study we explored suprathreshold contrast perception under conditions which simulated the luminance, contrast, and chromaticity of third-generation image intensifiers (as in the Aviator's Night Vision Imaging System or ANVIS). This was done by having subjects adjust the contrast of letters presented at everyday (photopic) light levels to appear equal in visibility to letters presented under simulated ANVIS conditions. The apparent contrast of letters seen through simulated ANVIS was reduced by a factor of two in comparison to normal photopic levels of presentation. Further analysis and consideration of previous studies suggested that this reduction in apparent contrast was limited to higher spatial frequencies (≥5 cycles/degree). These results help quantify limitations imposed by the human visual system when confronted by the low luminance and limited contrast of the ANVIS display.

Methods

Subjects

Seven adult volunteers (age 22 to 40; mean = 31 years) with normal vision and visual acuity corrected to 20/20 participated in this study. Six of seven subjects were emmetropic; one subject wore glasses during testing. Subjects viewed the display through a 3 mm artificial pupil and each was corrected for the viewing distance during testing (80 cm; +1.25D). Six of the seven subjects participated in the main experiment, and three of the subjects participated in control experiments.

Apparatus

Letter stimuli were generated on a high resolution color monitor. Temporal presentation, contrast, and chromaticity were under computer control. Screen luminance was measured with a calibrated photometer and stored in tabular form. Figure 1 shows the display used for the contrast matching experiment. The column of "E's" on the left panel simulated the isochromatic, green display of ANVIS. The luminance of this display was 0.6 fL which is midway in the range of ANVIS display luminances. Letters appeared as increments relative to the background with a fixed Michelson contrast of 11.3%. This contrast was used since it represents a moderate contrast above threshold likely to be encountered in a field environment. Only the green gun (phosphor) of the color monitor was used for this display to simulate the isochromatic, green ANVIS field. The column of "E's" on the right panel was presented at a higher background luminance (30 fL) which approximated normal photopic viewing conditions (Price and McLean, 1985). This display was generated by modulating the red, green and blue guns by equal amounts and therefore appeared achromatic (varied along a black-white dimension). The letters on the right display also appeared as increments relative to the background, but could be varied up and down in contrast by keyboard control. Each letter pair differed by a factor of two in size corresponding to Snellen letter sizes of 20/600, 20/300, 20/150, and 20/75, and dominant spatial frequencies of 1, 2, 4, and 8 cycles/degree.

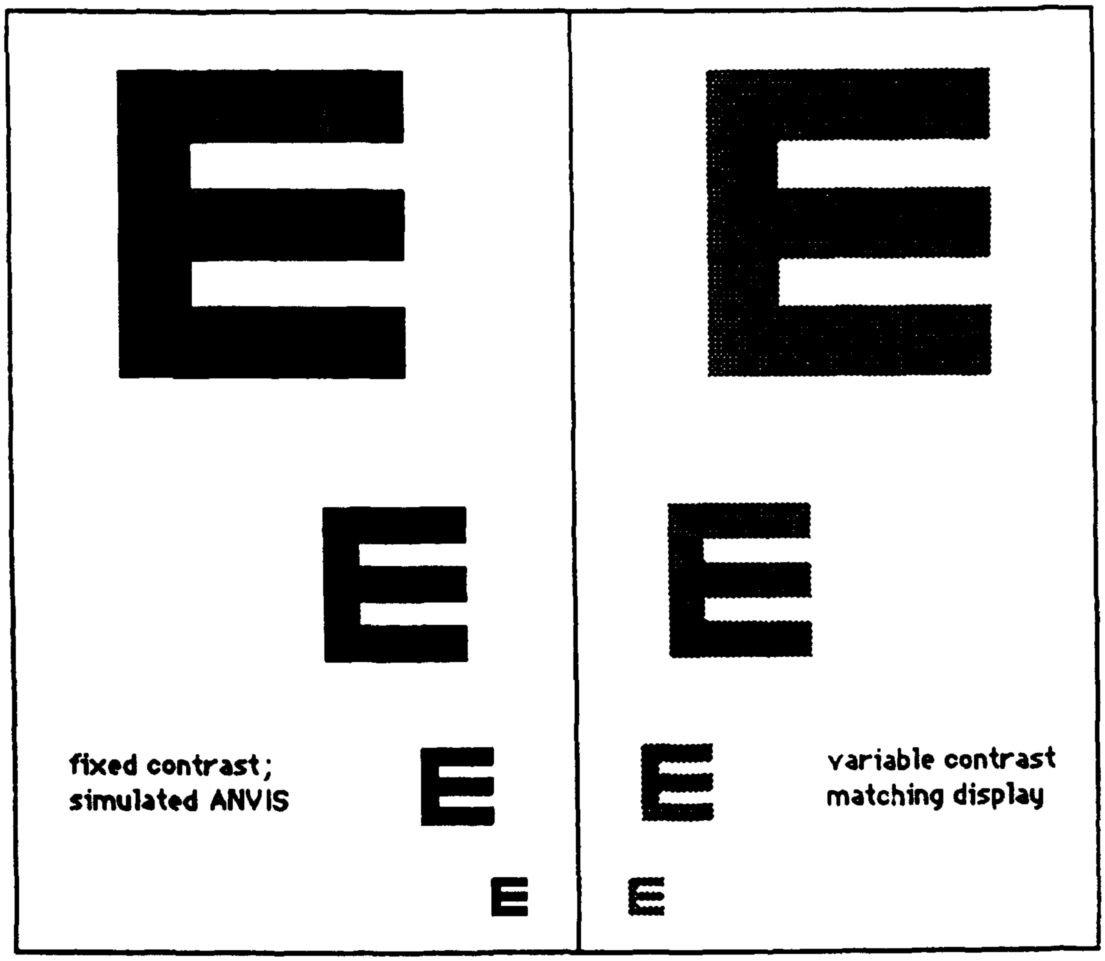

Figure 1. Contrast matching display used in the present experiment. The letters on the left were presented at a low luminance and fixed contrast to simulate the ANVIS display. The letters on the right were presented at a higher luminance corresponding to normal photopic conditions and were adjusted in contrast to match the letters on the left.

Experimental design and procedures

In this study each subject adjusted the contrast of letters in the normal photopic display to match the apparent contrast of letters in the simulated ANVIS display. The subject was seated comfortably in a darkened room 80 cm from the display which was viewed monocularly through a 3 mm pupil. Subjects were instructed to adjust the contrast of each letter on the right such that it appeared equally clear and equally different from its background as the corresponding letter on the left. Two keys (1 and 2) on a keyboard directly in front of the subject allowed them to increase or decrease right panel letter contrast in steps of approximately 3%. They were told to begin with the uppermost (largest) letter pair and to then continue downward matching each pair successively. This was repeated three times by each subject. The first run of four matches was regarded as practice, and the mean of the last two settings was computed as the subject's match for each of the four letter sizes. Within subject variability between settings was low (mean within-subject difference between settings = 0.4 ± 0.6 steps; mean variability in contrast = 1%). Because stimulus contrast was linearly related to keyboard values selected by the subject to achieve each match, subsequent computation of group mean data which revealed values between keyboard steps were converted to contrast values from the relation shown in Figure 2.

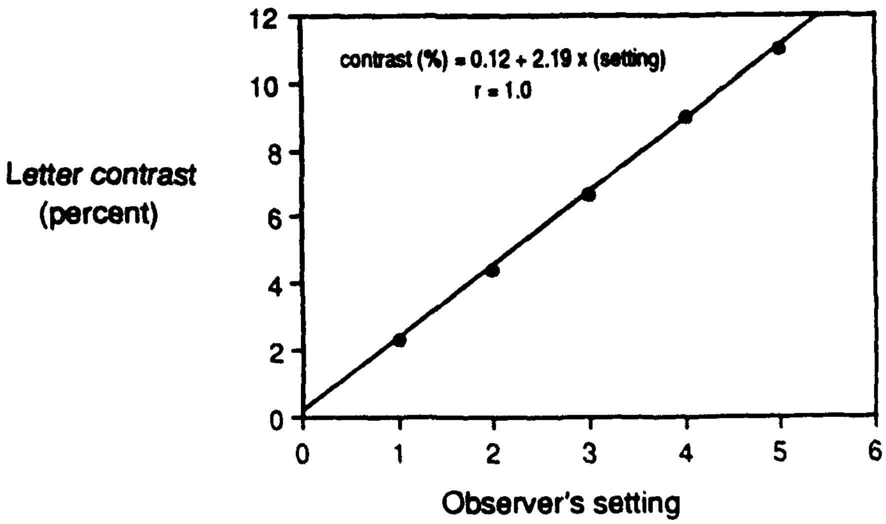

Figure 2. The linear relation between stimulus contrast and keyboard settings.

Results

Direct contrast matching

The main results of this study are shown in Figure 3. The mean contrast (±2SD; n=6 subjects) of letters on the normal photopic display which matched the apparent contrast of corresponding letters on the simulated ANVIS display is shown for a range of letter sizes. Log spatial frequency corresponding to the limb of each letter is depicted on the bottom, and Snellen letter sizes are shown at the top. The actual stimulus contrast of the ANVIS display, which was held constant throughout the experiment at 11.3%, is indicated by the broken horizontal line. Thus, Figure 3 shows that the apparent contrast of letters perceived under simulated ANVIS conditions is approximately 2X less than the actual letter contrast. That is, letters seen under simulated ANVIS conditions appear to have 2X less contrast than letters viewed under normal photopic conditions.

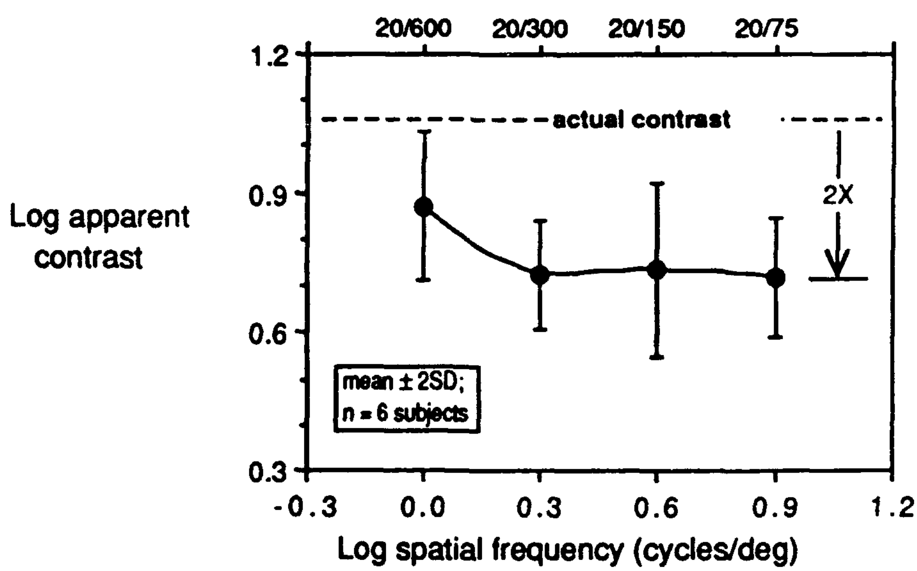

Figure 3. Direct contrast matching results. The mean (±2SD) log contrast of each variable contrast letter which matched the apparent contrast of the corresponding ANVIS letter is shown for the range of letter sizes. The dimension of each letter limb is indicated by log spatial frequency and corresponding Snellen letter sizes are shown at the top. The contrast of the ANVIS letters (11.3%) is indicated by the broken horizontal line. The apparent contrast of ANVIS letters was about 2X less than the actual contrast over a range of letter sizes.

It should be noted that the error bars in Figure 3 represent two standard deviations and thus include 95% of data points from the six subjects tested. Statistical comparison of each mean apparent contrast to the actual letter contrast revealed a highly significant difference (mean $t=10.0$; $p<0.001$) thus corroborating the reduction in contrast perception under simulated ANVIS conditions. A one-way ANOVA was performed to explore the difference between mean contrasts across the different letter sizes. While this revealed a marginally significant difference ($F=4.2$; $p<0.05$), further analysis with a series of paired t-tests indicated that this difference between letter sizes was limited to the largest letter tested (i.e., lowest spatial frequency). Thus, as is evident in Figure 3, the mean apparent contrasts of 20/75 to 20/300 letters were not significantly different ($F=0.04$; $p>0.95$) indicating that the reduction in contrast perception is relatively constant across letter size.

The luminance of the simulated ANVIS display was about 50X less than the luminance of the photopic matching display. Thus, it could be argued that the reduction in apparent contrast under ANVIS starlight conditions was caused by optical degradation of the retinal image due to increased pupillary size and/or inaccurate accommodation. However, all subjects were tested with a fixed pupil size (3 mm) and accommodation was neutralized by optically correcting for the viewing distance. Therefore, the reduction in contrast perception under ANVIS starlight conditions cannot be attributed to optical factors.

It is also possible that glare from the higher luminance display reduced the contrast of the ANVIS display, or that the adaptational demand of switching back and forth between the two different luminances affected contrast sensitivity. To explore these possibilities, two additional approaches were utilized to evaluate suprathreshold contrast perception: interocular and successive contrast matching.

Interocular contrast matching

The matching experiment was repeated on three subjects, but in this case the right and left displays (see Figure 1) were presented separately to the subject's right and left eyes. Hence the task involved matching the apparent contrast of ANVIS letters seen by the left eye by adjusting the contrast of the higher luminance letters seen by the right eye. The left and right displays were presented separately to each eye by attaching light-weight tubing to a trial frame which restricted the monocular fields of view to each half of the monitor screen. As in the main experiment, 3 mm artificial pupils and optical correction for the viewing distance were also used. Figure 4 shows mean results from three subjects plotted as specified for Figure 3. Although variability was greater in this smaller number of subjects, the same basic result was obtained. The apparent contrast of letters seen under simulated ANVIS starlight conditions was about 2X less than under typical photopic conditions. Because the right (high luminance) and left (low luminance ANVIS) displays were presented separately to each eye, local effects of glare and changes in retinal adaptation did not influence the results.

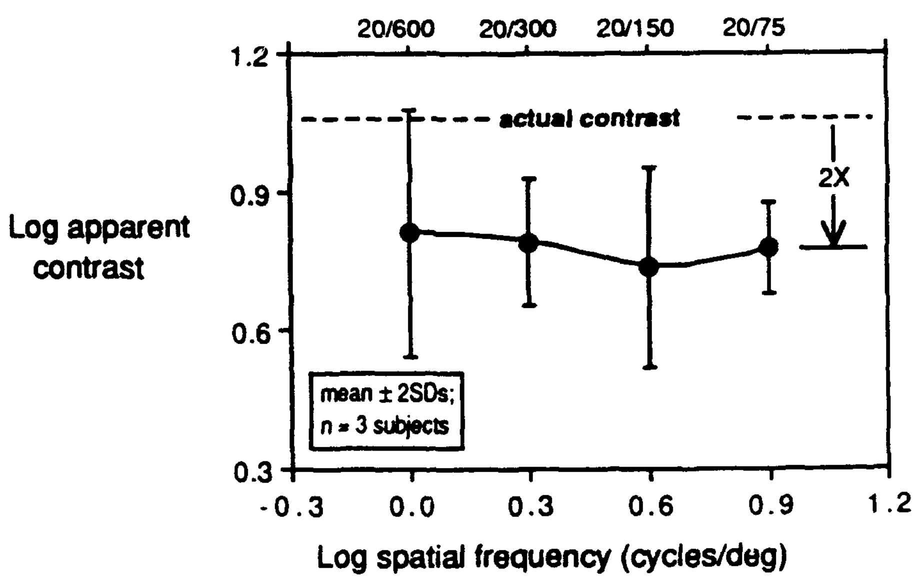

Figure 4. Interocular contrast matching results. The mean (±2SD) log contrast of each variable contrast letter which matched the apparent contrast of the corresponding ANVIS letter is shown for the range of letter sizes. Matches were made interocularly with the variable display visible to the right eye, and the ANVIS display visible to the left eye. Letter size and contrast are as specified in Figure 3.

Successive contrast matching

A final approach was used to further explore contrast perception under the simulated ANVIS conditions. In this experiment letters under the low luminance ANVIS and higher luminance conditions were presented successively rather than simultaneously. Each cycle of presentation began with a uniform, green field at the ANVIS luminance which lasted for a period of 20 seconds. A single letter E at the ANVIS luminance and contrast then appeared centered in the screen for a period of 5 seconds. This test letter was then replaced by a row of four E's of different contrasts at the higher photopic luminance used earlier. This matching display remained on for 5 seconds, and the subject's task was to select one of the four letter E's (numbered 1-4) which best matched the preceding, single ANVIS letter in terms of clarity and contrast. The next trial (20 s of uniform field, 5 s ANVIS test letter, 5 s matching display) then began. Letter size and the order of contrasts in the matching display were varied from trial to trial. Measurements were repeated three times with each of the four letter sizes. Three subjects were tested. Figure 5 shows mean apparent contrast plotted against a range of letter sizes as in Figures 3 and 4. The same essential result ensued wherein the apparent contrast of letters under simulated ANVIS starlight conditions was about 2X less than under normal photopic conditions. The fact that the reduction in apparent contrast was found with two different methods of measurement (simultaneous and successive matching) underscores the validity of this finding.

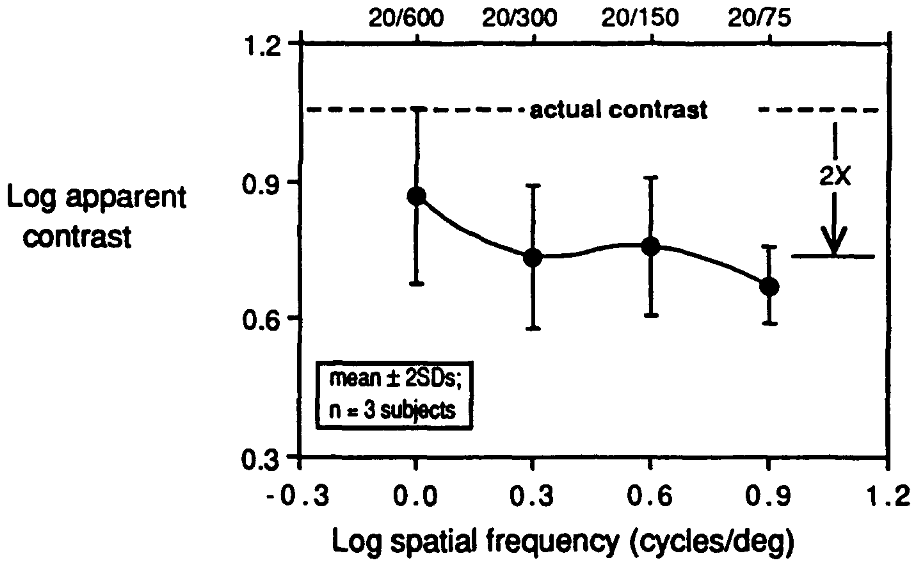

Figure 5. Successive contrast matching results. The mean (±2SD) log contrast of each variable contrast letter which matched the apparent contrast of the corresponding ANVIS letter is shown for the range of letter sizes. Successive matching was used to make each contrast match. Letter size and contrast are as specified in Figure 3.

Prediction of apparent contrast through ANVIS

Kulikowski (1976) derived a simple relation to quantify the apparent contrast (C_a) of a stimulus in terms of its physical contrast (C) and threshold contrast (T):

$$C_a = C - T$$

He went on to show that this relation can explain a number of suprathreshold conditions including differences in apparent contrast across luminance levels. In general, this relation suggests that threshold plays an important role in contrast perception at low contrasts (i.e., near threshold), but a less relevant role at higher, suprathreshold levels of stimulation. Thus, when physical contrast (C) becomes large relative to threshold (T), apparent contrast (C_a) approaches the physical contrast value. Yet, if physical contrast is close to the observer's threshold, then apparent contrast can be substantially less than the physical value (particularly when considered on a ratio or logarithmic scale). To determine whether this relation can explain the present results obtained with letters, recognition thresholds for each of the four letter sizes were determined for one subject using the method of adjustment. These values were then used in the equation shown above ($C_a = C - T$) to predict the photopic contrast which would match the fixed ANVIS contrast (11.3%). Table 1 shows the predicted contrasts and actual contrasts of the higher luminance letters which matched the fixed contrast ANVIS letters. In all cases the predicted matching contrast is higher than the actual values. This indicates that the equation described above ($C_a = C - T$) overestimates the perceived contrast of ANVIS letters. Perhaps the low luminance and isochromatic nature of the ANVIS display impose constraints on contrast perception which are not manifest in Kulikowski's equation. It is also possible that the spatial frequency channels involved in recognition and matching of letters are different for the photopic and simulated ANVIS light levels. Then the task could have involved matching across both luminance and spatial frequency mechanisms making it less amenable to models based on spatially simple stimuli such as sinusoidal gratings.

Table 1.

Predicted and actual contrasts to match ANVIS display.

Snellen letter size	Predicted matching contrast (%)	Actual matching contrast (%)
20/600	10.9	7.4
20/300	10.8	5.3
20/150	9.3	5.4
20/75	7.4	5.2

Discussion

This study demonstrated that the apparent contrast of letters seen under simulated ANVIS conditions is reduced by a factor of two when compared to letters viewed under normal photopic conditions. This reduction in visibility was not limited to a single stimulus, but was found for a range of letter sizes. Because accommodation and pupil size were controlled throughout the study, differences in contrast perception could not be attributed to preneural optical factors. The fact that similar results were obtained with several different methods of measurement (monocular and interocular simultaneous matching; successive matching) indicated the validity of our finding. The reduction in letter visibility under simulated ANVIS starlight conditions is apparently neural in origin.

The primary difference between the simulated ANVIS and photopic displays used in the present study was the difference in luminance (the photopic display was about 50X more intense than the ANVIS display). Hence, the difference in apparent contrast of letters seen under the two conditions is probably related to this luminance difference. Kulikowski (1976) and Hess (1990) have also reported a reduction in suprathreshold contrast perception at lower levels of luminance. In these studies sinusoidal gratings were used which are less complex than letters in terms of their spatial frequency content. Both studies reported findings comparable to our results for spatial frequencies ≥5 cycles/degree (see Figure 1b in Kulikowski, 1976; Fig. 9c in Hess, 1990). However, at lower spatial frequencies Hess (1990) found little attenuation of apparent contrast at luminance values similar to those used in the present study. This suggests that the matching task used in our study primarily involved equating the visibility of moderate and higher spatial frequency components of the letters. Thus, while it is appealing to use familiar, recognition targets such as letters to assess vision, the spatial complexity of these targets can reduce the precision with which we identify the underlying spatial mechanisms. Perhaps a better description of the findings reported herein is that visibility of moderate and smaller-sized letters is reduced under the low light levels of the ANVIS display.

While our results may not be applicable to lower spatial frequencies, it is clear that both threshold and suprathreshold contrast perception of higher frequencies is reduced at the low luminance of the ANVIS display. Under low light levels such as starlight conditions it is likely that the contrast of objects seen through ANVIS is attenuated (Verona, 1985; Verona and Rash, 1989) making contrast perception more dependent on the observer's thresholds for various spatial frequencies. Because psychophysical thresholds for higher frequencies are increased at low light levels, the visibility of detail is diminished making object recognition equivocal. This limitation is imposed by the visual system and reflects minimum light levels necessary to stimulate cone-driven, higher spatial frequency receptive fields. Other factors at low levels of stimulation, such as the presence of electro-optical noise, also contribute to degradation of vision through ANVIS. Research is underway to determine electro-optical and human constraints on visual perception through image intensifying devices.

Conclusions

1. The apparent contrast of letters viewed under simulated ANVIS conditions was reduced by a factor of two when compared to normal photopic levels of stimulation.

2. This relative attenuation in suprathreshold contrast perception was attributed to limitations of the human visual system in processing higher spatial frequencies at low light levels.

3. The results help discriminate between human and electro-optical constraints on vision through ANVIS under low levels of ambient stimulation.

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